Stress Analysis of Gas Turbine Wheel

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Abstract

A Turbine wheel (rotor) plays a significant role in gas turbine. The rotor on which the blades are mounted transmitting this motion holds a key point to better efficiency of gas turbine. Thus more focus should be given to the design of the turbine rotor.

Gas-turbine discs are normally operated at high temperatures. The hot gases contact the blades and the rim of the turbine rotor and thus maintain the rim at high temperature. The temperature gradient at rim and central portion of rotor causes the sources for thermal stresses. The disc is expected to perform well in spite of all the stringent operating conditions [1] .The Advancement in gas turbine materials has been always a major concern—higher their capability to with stand elevated temperature service, produce lower stresses, light weight and more the engine efficiency.

In this paper, an attempt is made to determine the stresses like Thermal, Structural, Radial and other stresses with different materials. The Analytical analysis is carried out by using ANSYS to determine the intensity of stresses.

1. Introduction

The important role of the turbine wheel in the gas turbine has directed much attention to the analysis of stresses in rotating turbine wheels with temperature gradient. Since heat is conducted from the buckets into the disc, a radial temperature gradient exists in the disc. The outer portions are at a relatively high temperature and would expand if free, but they are held back by the cooler inner portions. This results in tensile thermal stresses in the radial direction but compressive thermal stresses in the tangential direction. Thermal gradients developed during thermal transients are the key sources of stresses generation in the rotor [2].

Thermal stresses may also result from an axial temperature gradient. At the rim the centrifugal stresses are all tensile but thermal tangential stresses takes on large compressive values. The low margin of the safety at the rim is due to the presence of resultant compressive stresses. Excessive values of such stresses often cause plastic flow of disc during the engine operation and when the disk cools, a system of tensile stresses is set up that can cause rim cracking. Because such cracks usually progress rather slowly, serious troubles from this source can, in most cases, be forestalled by removal of the wheel from service. The thermal and centrifugal stresses are both tensile at the center; in the event that these stresses become excessive, a sudden rupture of the rotor would probably occur. Discs are therefore usually designed to have larger margin of safety at the center than at the rim.

2. STRESS ANALYSIS OF ROTATING GAS TURBINE WHEEL

In a thin rotating disc of variable thickness, the state of stress at any radius can be completely defined by the two principal stresses, the radial and tangential stresses σ_r and σ_t respectively. Two equations are therefore necessary to determine the two unknown stresses. The first of these equations can be obtained from the conditions of the equilibrium of the element of the disc. The second from, the compatibility conditions, which are mathematical statements of the interrelation between the radial and tangential strains in a symmetrical disc. The equilibrium and compatibility equations results in differential form defining the relations between the stresses at radius r and those at radius infinitesimally removed from r. The unknown stress can be determined by the boundary conditions at the rim of the disc where the radial stress is equal to the centrifugal blade loading [3].

Lets

σ_r = radial stress, N/m^2

σ_t = hoop stress, N/m^2

r = radius of disc at any point, m

t = thickness of disc at radius r, m

μ = poison's ratio

ρ = density of rotor material, Kg/m^3

E = Young's modulus

ω = Angular velocity

R1 = Inner radius

R2 = Outer radius

Radial stress

$$\sigma_r = \frac{E}{1-\mu^2}\left[a\, r^2 (3+\mu) + b_1(1+\mu) - b_2(1-\mu)/r^2\right]$$

Tangential stress

$$\sigma_t = \frac{E}{1-\mu^2}\left[a\, r^2(1+3\mu) + b_1(1+\mu) + b_2(1-\mu)/r\right]$$

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Equivalent stress $\sigma_v = (\sigma_r^2 - \sigma_r \sigma_t + \sigma_t^2)^{1/2}$

Radial dis placement $y = a r^3 + b_1 r + b_2/r$

Where,

$$b_1 = \frac{\left[\sigma_2 (1-\mu^2) R_2^2/E - a(3+\mu)(R_2^4 - R_1^4)\right]}{(1+\mu)(R_2^2 - R_1^2)}$$

$$b_2 = \frac{R1^2}{1-\mu}\left[a R_1^2 (3+\mu) + b_1 (1+\mu)\right]$$

$$a = -\rho\omega^2 (1-\mu^2)/ 8E$$

3. Turbine wheel materials:

Many thousands of supercharger turbine discs were made of Cyclops 17W, alloys such as A-286 are used. Later Timken "16-25-6" steel was used extensively. Now Alloy 718 Nickel Base alloys are using and alloy 706 is the advanced material.

3.1 Alloy 718:

Alloy 718 is a precipitation hardenable nickel based alloy designed to display exceptionally high yield, tensile, and creep rupture properties at temperature up to 1300F Alloy 718 is Austenitic structure, precipitation hardening generate "γ" made it excellent mechanical performance. Grain boundary generate "δ" made it the best plasticity in the heat treatment. This alloy has extreme resistance to stress corrosion cracking and pitting ability in high temperature or low temperature environments, especially the resistance against oxidation at the high temperature.

Chemical composition:

Ni	Cr	Fe	Mo	Mg	C	Si	S
52.5	19.0	Bal	3.0	0.35	0.08	0.35	0.015

Characteristics of alloy 718:

- Workability
- High tensile strength, endurance strength, creep strength and rupture strength at 700°C.
- High inoxidability at1000°C.
- Good welding performance
- Steady mechanical performance in the low temperature.

The elevated temperature strength, excellent corrosion resistance and workability at 700°C properties made it use in a wide range of high requirement environments.

- Steam turbine
- Liquid-fuel rocket
- Cryogenic engineering
- Acid environment
- Nuclear engineering

3.2 Timken steel:

Timken steel is fine grained alloy steel that combines medium carbon content with a robust balance of chromium, nickel and molybdenum for enhanced hardenability. It was originally developed as an alloy to provide ultra high transverse strength and toughness for air craft applications with excellent wear resistance. Typical applications include Drive shafts, crank shafts, turbine components, connecting rods etc.

Chemical composition:

Cr	Ni	Mo	C	Mn	Si	N	Fe
16	25	6	0.08	1.5	0.5	0.15	Bal.

3.3 Alloy 706:

This Nickel-based, precipitation hardened alloy is the newest to be used in turbine wheel application. It has very significant increase in stress rupture and tensile yield strength compared to other alloys. This alloy is similar to Alloy 718 and it contains somewhat lower concentrations of alloying elements than alloy 718 and is therefore possible to produce very large ingot sizes of turbine wheels. It is a precipitation hardened alloy that provides high mechanical strength in combination with good fabricability. It has excellent resistance to post weld strain age cracking.

Chemical composition:

Ni	Cr	Fe	Ti	C	Cu	Mn	Si	S	co
42	15	6	1.7	0.06	0.3	0.35	0.35	0.015	1.0

Characteristics:

- Good machinability
- High creep rupture strength
- Excellent weldebility

4.1 Turbine wheel materials and their properties:

	Timken Steel	Alloy 718	Alloy 706
Yield stress N/mm2	620	1375	1300
Density Kg/m3	7850	8190	8080
Poisson ratio	0.3	0.35	0.382
Young's modulus N/mm2	2.1×10^{11}	2.1×10^{11}	2.1×10^{11}
Thermal conductivity w/m-k	3.6	11.4	12.5
Specific heat J/Kg/ ^{0} c	486	435	444

4. Turbine wheel specifications:

Mass of each blade	: 0.92 kg
No. of blades	: 100
Inner radius of TW (R1)	: 0.0445m
Outer radius of TW(R2)	: 0.45355m
Angular velocity of TW	: 534 rad /sec

5. Theoretical stress calculations for different materials:

5.1 Steel:

Radius mm	Tangential stress N/mm^2	Equivalent stress N/mm^2	Displacement mm
45	233.68	233.68	0.09
116	221.46	203.50	0.11
225	199.82	186.35	0.14
450	118.075	104.92	0.19

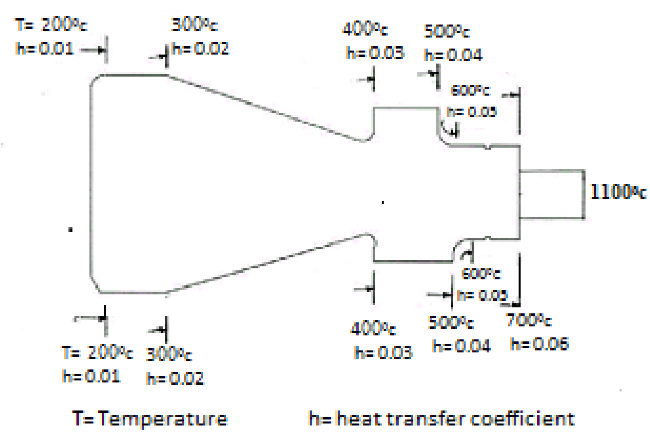
5.2 Alloy 718:

Radius mm	Tangential stress N/mm2	Equivalent stress N/mm2	Displacement mm
45	219.81	219.813	0.083
116	207.19	190.273	0.095
225	183.18	170.354	0.127
450	91.34	86.192	0.139

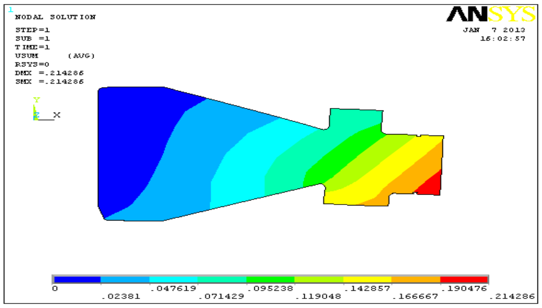
5.3 Alloy706:

Radius mm	Tangential stress N/mm2	Equivalent stress N/mm2	Displacement Mm
45	179.45	179.45	0.062
116	167.68	153.69	0.078
225	143.26	132.05	0.095
450	85.5	80.85	0.102

6. FEM analysis through ANSYS:

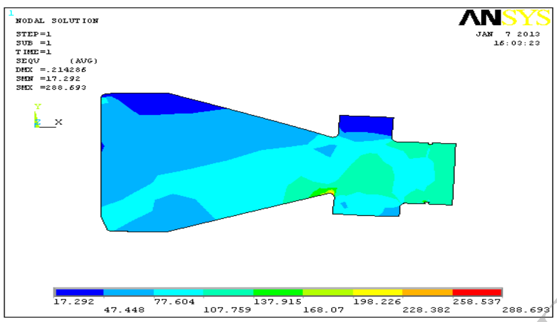


6.1 **Boundary conditions**



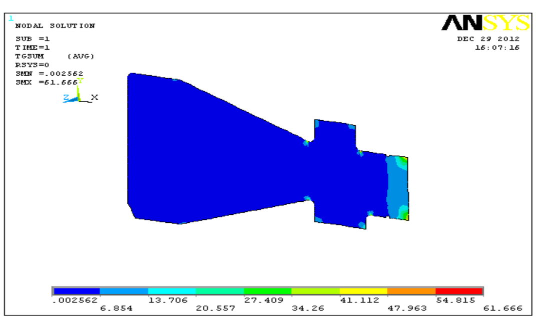
6.2 Deformation of Turbine Wheel for steel.

The deformation of turbine wheel is found maximum 0.214mm at the rim.

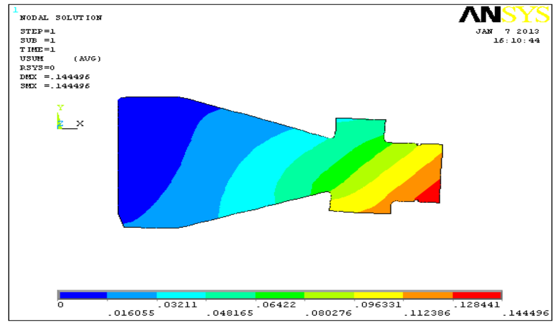


6.3 Over all stresses of gas turbine wheel for Timken steel.

The maximum stresses are found to be 258.537N/mm^2.

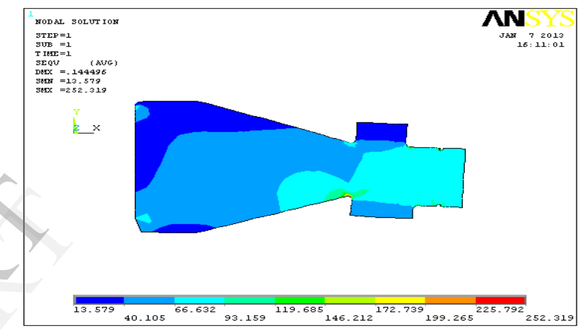


6.4 The Maximum temperature dissipation for steel is 61.66 ^{0}C/meter.



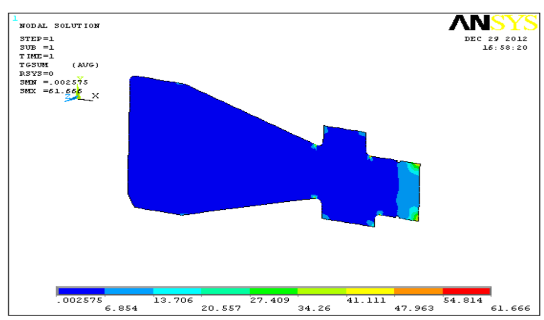
6.5 Deformation of Wheel for Alloy 718

The deformation of Turbine Wheel is found maximum 0.144mm at the rim.

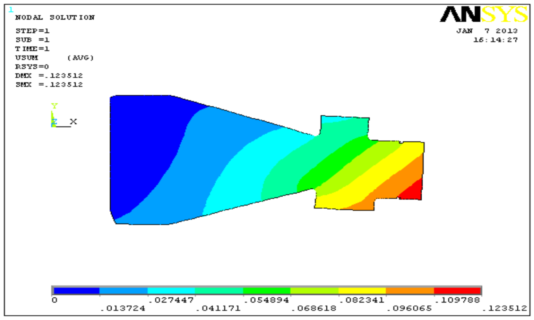


6.6 Overall stresses of gas turbine wheel for alloy 718.

The maximum stresses are found to be 252.219N/mm$^{2.}$

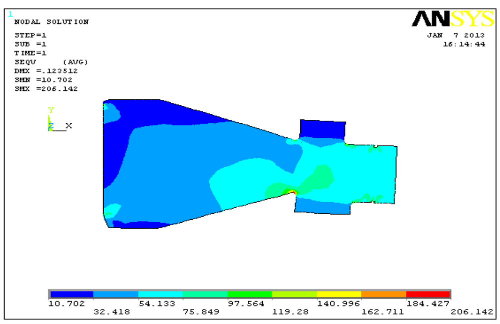


6.7 The Maximum temperature dissipation for alloy 718 is 61.66 ^{0}C/meter.



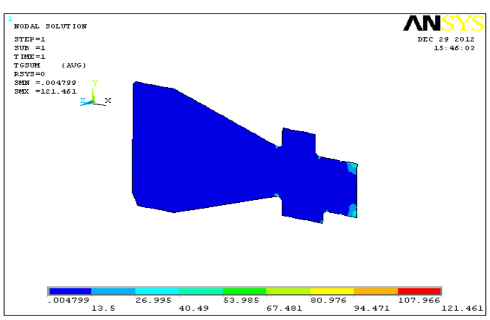
6.8 Deformation of Turbine Wheel for Alloy 706

The deformation of Turbine Wheel is found maximum 0.123mm at the rim.



6.9 Overall stresses of gas turbine wheel for alloy 706.

The maximum stresses are found to be 206.142N/mm^{2}.



6.10 The Maximum temperature dissipation for alloy 718 is 121.461 ^{0}C/meter.

7.0 Results and Discussion:

	Deformation mm	Stress N/mm^2	Temp. dissipation ^{0}C /m	Strength N/mm^2
Steel	0.214	258.539	61.66	620
Alloy 718	0.144	252.219	61.66	1375
Alloy 706	0.123	206.141	121.46	1300

Table: 1 Results obtained by ANSYS

	Deformation mm	Stress N/mm^2	Strength N/mm^2
Steel	0.190	233.68	620
Alloy 718	0.139	219.813	1375
Alloy 706	0.100	179.45	1300

Table.2. Results obtained by Mathematical Approach

- From the table 1, it was found that the results obtained by ANSYS are nearly equal to the theoretical calculations.

- From the table 1, it is found that the deformation of Alloy 706 is low as 0.123 mm, which is nearly equal to the mathematical approach, while the deformation of Alloy 718 is 0.144 mm and Timken steel is 0.139 mm.
- From the table 1, it is found that the overall stress of Alloy 706 is 206.141 N/mm^2 which is small comparing to the Timken Steel (258.539 $N/mm^{2)}$ and Alloy 718(252.219 $N/mm^{2)}$.
- Temperature dissipation of Alloy 706 is high 121.46 c°/m which is good when comparing to Timken Steel and Alloy 718(both 61.66 ° c/m)
- The yield strength of Alloy 706 is also high i.e. 1300 N/mm^2 which is good comparatively Timken Steel (620 $N/mm^{2)}$ and Alloy 718(1300 N/mm^2)
- The Alloy 706 has good machinability character with moderate cost.

7.1 Conclusion:

The analysis was carried out for gas turbine wheel which was done using ANSYS. It is concluded that Inconel 706 alloy was found better results than other two alloys, 718 alloy and Timken steel.

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